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Chilled Water Storage Cooling System at Fort Jackson, SC

by
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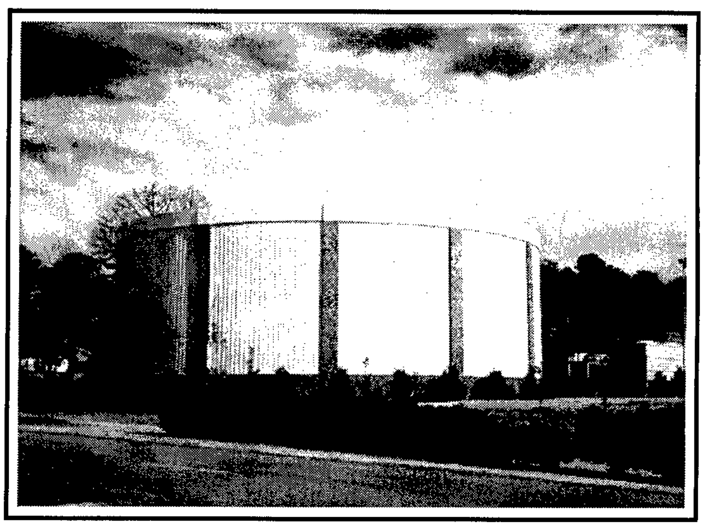
For many Army installations, the electrical demand charge of their utility bills can be as high as 50 percent of the total bill. One effective way to reduce peak electrical demand and electrical utility costs is by use of storage cooling systems. To curb the anticipated growing cost of the electrical utility at Fort Jackson, the engineers at the Directorate of Public Works (DPW), Fort Jackson, decided to install a 2.25M-gal capacity chilled water storage (CWS) cooling system for the Energy Plant No. 2, which serves more than half of the Fort's cooling load. During the first year operation (1996-1997), the system saved about $0.43M in electrical utility bill charges from reduced on-peak electrical demand and reduced energy consumption for cooling. This report documents the design, construction, operation, and performance of the system.



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For many Army installations, the electrical demand charge of their utility bills can be as high as 50 percent of the total bill. One effective way to reduce peak electrical demand and electrical utility costs is by use of storage cooling systems. To curb the anticipated growing cost of the electrical utility at Fort Jackson, the engineers at the Directorate of Public Works (DPW), Fort Jackson, decided to install a 2.25M-gal capacity chilled water storage (CWS) cooling system for the Energy Plant No. 2, which serves more than half of the Fort's cooling load. During the first year operation (1996-1997), the system saved about $0.43M in electrical utility bill charges from reduced on-peak electrical demand and reduced energy consumption for cooling. This report documents the design, construction, operation, and performance of the system.

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Foreword

This study was conducted for the Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Project 40162784T45, "Energy and Energy Conservation"; Work Unit UL-X28, "Advanced Cooling Technologies." System operation support during the 1997 cooling season was funded by Fort Jackson through Military Interdepartmental Purchase Request (MIPR) No. 76CRL0020, "Re-Commissioning of Chilled Water Storage Cooling System for Central Energy Plant No. 2 at Fort Jackson." The technical monitor was Tim Gordon, CEMP-ET. The Fort Jackson technical POC was Jerry Fuchs, ATZJ-PWO-E.

The work was performed by the Utilities Division (UL-U) of the Utilities and Industrial Operations Laboratory (UL), U.S. Army Construction Engineering Research Laboratories (CERL). The CERL Principal Investigator was Dr. Chang W. Sohn. The designer of the system was Michael Gruber, CESAS-EN-DO. Martin J. Savoie is Chief, CECER-UL-U; John T. Bandy is Operations Chief, CECER-UL; and the responsible Technical Director is Gary W. Schanche, CECER-TD. The CERL technical editor was William J. Wolfe, Technical Resources.

Dr. Michael J. O'Connor is Director of CERL.

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1 Introduction

Background

In most Army installations, the electrical demand charge equals more than one-third of the total electrical utility bill. For many installations, the demand portion is as high as 50 percent of the total bill (Sohn and Cler 1989). One effective way to reduce peak electrical demand and thereby to reduce electrical utility costs is through the use of storage cooling systems (Sohn 1992). Installation and use of chilled water storage systems as a way to meet cooling needs and reduce energy costs are well documented. An industry-wide design guide for storage cooling systems has been published by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE 1993). The U.S. Army Corps of Engineers published a guide specification for military construction of storage cooling systems in 1996 (CEGS-15848; HQUSACE 1996).

A detailed analysis of end-use of electricity at Fort Hood, TX showed that cooling is responsible for 54 percent of the total peak demand of electricity (Akbari and Konopacki 1995). Fort Jackson is typical among Army installations, where summertime air conditioning accounts for a significant portion of electrical utility bills. During calendar year 1989 (CY89), the yearly electrical utility cost for Fort Jackson was \$4.5M, the demand charge was \$2.2M (49 percent), and the energy charge was \$2.3M (51 percent). The demand portion of the bill, as well as the total cost of the electrical utility cost, kept on growing in the following years. By CY96, the demand charge was \$2.7M, or 51 percent of the total electrical bill of \$5.3M.

To curb the anticipated growing cost of the electrical utility at Fort Jackson, the engineers at Directorate of Public Works (DPW), Fort Jackson, decided in early 1990 to install a chilled water storage (CWS) cooling system for the Energy Plant No. 2, which serves more than half of the Fort's cooling load. The U.S. Army Corps of Engineers Construction Engineering Research Laboratories (CERL) conducted a feasibility study in 1990. The results showed a simple payback of a CWS cooling system less than 5 years (Sohn 1990). Based on the results of the study, the Army Energy Conservation Investment Program (ECIP) funded the project in fiscal year 1993 (FY93). The South Carolina Electric and Gas

Company offered an incentive program for the thermal storage at Fort Jackson at a rate of $300/kW deferred (Memorandum of Understanding [MOU] 1995). The one-time incentive award shortened the system payback time to less than the time predicted in the earlier feasibility study.

Objective

The objectives of this study were: (1) to document the design, construction, and operational performance of a CWS cooling system at Fort Jackson, SC, (2) to provide a design, construction, and operation reference on CWS cooling systems for Army engineers, and as a result, (3) to assist Fort Jackson DPW engineers to further improve system operation.

Approach

A description of the project was made from the design and construction of the system to the operation and performance analysis up to the second year of operation. The system's economic performance was analyzed using monthly electrical utility bills from 1994 through 1997. The system energy performance was measured by the on-site instrumentation with the EMCS system at Fort Jackson. Actual system payback period was calculated by the total project cost spent and the annual savings in the electrical utility cost as reflected in the monthly electrical bills during the first year of system operation.

Mode of Technology Transfer

A summary of this work was presented to the U.S. Army Corps of Engineers 1998 Electrical and Mechanical Engineering Training Conference (Sohn, Fuchs, and Gruber 1998). It is also recommended that the information in this report be incorporated into the Corps of Engineers guide specification on chilled water storage cooling systems. For the U.S. Army installation engineers, this report can serve as a reference for project development and implementation of chilled water storage cooling systems.

Units of Weight and Measure

U.S. standard units of measure are used throughout this report. A table of conversion factors for Standard International (SI) units is provided below.

SI Conversion Factors		
1 in.	=	25.4 mm
1 ft	=	0.305 m
1 yd	=	0.9144 m
1 sq in.	=	6.452 cm^2
1 sq ft	=	0.093 m^2
1 sq yd	=	0.836 m^2
1 cu in.	=	16.39 cm^3
1 cu ft	=	0.028 m^3
1 cu yd	=	0.764 m^3
1 gal	=	3.78 L
1 lb	=	0.453 kg
1 kip	=	453 kg
1 psi	=	6.89 kPa
°F	=	(°C x 1.8) + 32
1 ton (cooling)	=	12,000 BTU/hr

2 System Design and Construction

System Design

The system was designed by the U.S. Army Corps of Engineers Savannah District Office (CESAS) during FY93 in cooperation with DPW Fort Jackson and CERL.

Design Goal

The design goal of the chilled water storage (CWS) system for the Central Energy Plant (CEP) No. 2 at Fort Jackson was to shift operation of the four 120-ton chillers, from the summer on-peak hours (1300-2100, Monday-Friday excluding holidays) to off-peak hours. Recall that Fort Jackson has a master meter for measuring the installation-wide electrical demand for billing purposes. Figure 1 shows the hourly demand profile for the peak day in 1989.

Based on the new chiller rating of 0.64 kW/ton, turning off the four chillers (1200 ton each) at CEP No. 2 would reduce the electrical demand (P) by:

$$P = 4*1200 \text{ (ton)}*0.64 \text{ (kW/ton)} = 3072 \text{ (kW)}$$

According to the hourly demand profile shown in Figure 1, reduction of 3000 kW in demand could be achieved by turning off the four chillers from 1300-1800 hours. Therefore, the goal of the system design was to shift the electrical demand of 3000 kW from on-peak to off-peak periods.

Central Energy Plant No. 2 Operating Conditions

CEP No. 2 has four chillers, each rated at a 1200-ton capacity. CEP No. 2 serves more than half of the major buildings at Fort Jackson. Main supply lines branch from the plant in two zones. The total flow rate for CEP No. 2 is 8300 gal/minute (gpm) for the two zones, Zone 1 and Zone 2. The normal differential temperature of the chilled water is 12 °F with supply water temperature of 42 °F, and return water temperature of 54 °F. At night, the plant has a minimum of 2000 ton of cooling capacity to charge the tank.

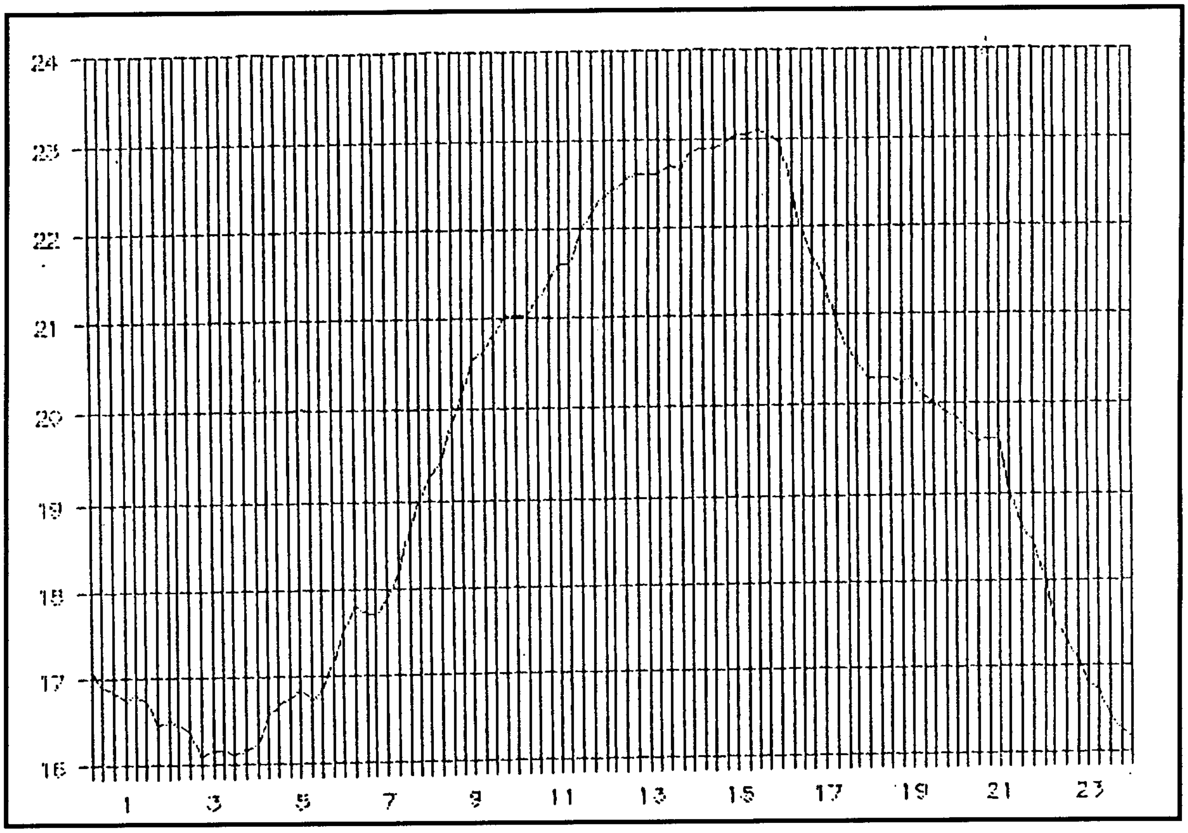

Figure 1. Hourly demand (in MW) on the peak day in 1989 (12 July 89).

Recall that CEP No. 2 serves more than half of the major buildings at Fort Jackson, which requires cooling round the clock.

Tank Sizing

The storage capacity of the tank should be large enough to store enough cooling to meet the cooling demands of CEP No. 2 for a selected period of a day. Based on the operational data from CEP No. 2, the integrated cooling load from 1300 to 1800 hours was estimated to be 16,000 ton-hr. With a 5 percent safety factor, the design cooling capacity (Q) of the storage tank was determined to be:

$$Q = 16{,}800 \text{ ton-hr}$$

The storage volume (V) of the tank is determined by the cooling capacity (Q), differential temperature between the supply and the return water (dT), and the figure-of-merit (FOM) of the storage tank. For a storage tank with well designed diffuser system, the FOM is recommended to be 0.9. (ASHRAE 1993). The

temperature differential for CEP No. 2 is 12 °F. Based on the these data, the volume of the storage tank was determined by:

$$V = Q/[c_p * dT * FOM]$$

$$= 16800\ (\text{ton-hr}) * 12000\ (\text{Btu/ton-hr})/[1 (\text{Btu/lbm °F}) * 12\ (\text{°F}) * 0.9 * 8.36\ (\text{lbm/gal})]$$

$$= 2.232\text{M (gal)}$$

The volume of the storage tank was determined to be 2.25M gal.

Tank and Diffuser Design

Due to the multiple competing options in the market (such as concrete or steel tank, and linear or radial diffuser), the CESAS bid specifications prescribed the functional requirements for the tank. The functional requirements included the storage volume, the storage cooling capacity, and the design of diffuser system as well as the other requirements such as aesthetic requirements from Fort Jackson. A particular aesthetic requirement was the height of the tank, which was not to exceed that of the nearby facility. The maximum height of the water column in the tank was limited to 40 ft. The bidders were requested to provide the details of the design of their choices, and the designs were subjected to the approval from the design team of the Savannah District Office, Fort Jackson, and CERL. The important characteristics of the approved design follow.

Tank Configuration. Tanks with low surface-to-volume ratios have a lower degree of thermal loss and have a lower cost per ton-hour of stored cooling construction cost. Therefore, flat-bottomed vertical cylinders are favored. Concrete tanks with height-to-diameter ratios between 0.25 and 0.33 represent a good compromise between a low-cost short tank and a tall tank that provides the best thermal stratification (ASHRAE 1993). Other factors must also be considered when determining tank dimensions, such as required flow rates and dimensions of the diffuser, and site conditions. The allowable bearing capacity of the soil as well as special architectural concerns should be taken into consideration. One particular criterion for the tank design at Fort Jackson was that the height of the tank not exceed the height of the tallest structure in its vicinity. A 40-ft tank water level, with a maximum tank height at 44 ft, was chosen. The resulting diameter was calculated as:

$$H = 40\text{ ft}$$

$$D = 2*(V/\pi H)^{(1/2)}$$

$$= 2*((2{,}25\text{M gal})/(7.48\text{ gal/cu ft})(\pi)(40\text{ ft}))^{1/2} = 98\text{ ft}$$

An aboveground cylindrical concrete tank was chosen with a 40-ft water level and 98-ft diameter. The resulting tank height-to-diameter ratio was 0.41, which favors thermal stratification in the tank. The tank was built on a reinforced concrete ring wall. A reinforcing steel rod skeleton was constructed and an encased inner steel shell was attached to the skeleton. Shotcrete was applied and allowed to cure and insulation was added to the walls. A synthetic stucco-covered exterior was added to the exterior of the tank for aesthetic reasons. Table 1 summarizes tank design characteristics. Figure 2 shows a diagram of the tank, including its elevation. Figure 3 shows the Tank Plan. An earlier paper reported to the *1995 USACE Electrical and Mechanical Engineering Training Conference* (Burch 1995) discusses the tank's design in detail.

Internal Diffuser Design. A chilled water storage tank needs diffusers to introduce water into the tank without creating disturbances in the fluid that could result in the deterioration of the thermocline. During charging the tank, a gravity current of cool, dense water is produced by the lower diffuser near the tank floor, and is spread horizontally. Similarly, a gravity current of less dense warm water is produced near the top of the tank by the upper diffuser during discharge. Octagonal diffusers, formed from eight straight sections of pipe connected with 135-degree elbows, have proved successful in the past for creation and maintenance of the thermocline in the tank. Octagonal diffusers with both the lower and upper array consisting of four rings were chosen to ensure proper stratification. The upper and lower diffusers were identical in shape. A maximum of 20 psid pressure loss from inlet flange to outlet flange was specified, as well as design flow rates of 4,000 gpm (charging) and 8,000 gpm (discharging). Due to the competing technologies and builders in the market, the CESAS design left the actual design of the internal diffuser to the contractor to be selected through an open bidding. However, the performance of the diffuser was prescribed to meet the industry recommendation of the maximum inlet Reynolds Number to be less than 2000, and the Froude number less than 2 (ASHRAE 1993). The final design of the diffuser by the successful bidder was a quadruple octagonal diffuser system with the total linear diffuser length of 851 ft (Figure 4). Note that Figure 4 is intended to convey the general configuration of the diffuser system, not the fine details of each segment.

Table 1. Chilled water tank specifications.

Cooling capacity	16,800 ton-hour
Size	2.25M gal
Mean diameter	98 ft
Water level height	40 ft
Height-to-diameter ratio	0.41
Plan area	7,543 sq ft
Vertical core wall thickness	Tapers from 7 ¼ in. at bottom to 3 ½ in. at top including 1 in. cover over steel shell diaphragm.
Vertical wall material	Prestressed composite wall (steel shell/shotcrete) with 5 in. thick rigid Styrofoam insulation glued to concrete tank and finished vee rib outer sheeting; brick outer shell for bottom 7 ft-8 in.
Dome shell	3-in. thick concrete with expanded polystyrene insulation
Floor	5-in. concrete with painted outer surface

Table 2 lists detailed characteristics of the installed diffuser system.

An underground 24-in. chilled water supply pipe and 24-in. chilled water return pipe connected the storage tank to CEP No. 2. The flow branched into two separate 20-in. PVC pipes and was carried to the first octagonal ring. All octagonal ring diffusers were 14-in. PVC. Total diffuser length, which represented the sum of the four octagonal rings, was 851.0 ft. The sections of pipe had slots cut into them, through which the flow was diffused into the tank. The area of each slot was set such that the sum of the slot areas in each diffuser pipe equaled the cross-sectional diffuser pipe area. The calculation of an effective diffuser length based on twice the total diffuser length was necessary to account for the fact that the water is diffused into the tank in both the radial inward and radial outward directions. Total flow rate was based on 125 percent of the design discharge rate and was calculated as:

(8,000 gpm)(1.25)/((60 sec/min)(7.48 gal/cu ft)) = 22.3 cu ft/sec

Since the diffuser design included 32 sections of pipe, each diffuser pipe flow rate was calculated to be:

(22.3 cu ft/sec)/32 = 0.7 cu ft/sec

Mixing in the tank is also influenced by the inlet flow rate per unit length of diffuser, expressed by the Reynolds number. A maximum Reynolds number of 2,000 was specified for the design of the diffuser. The Reynolds number is defined as the flow rate per foot of diffuser length divided by the kinematic viscosity of inlet water. The total diffusion rate was:

22.3 cu ft/sec/1,702 ft = 0.01310 sq ft/s

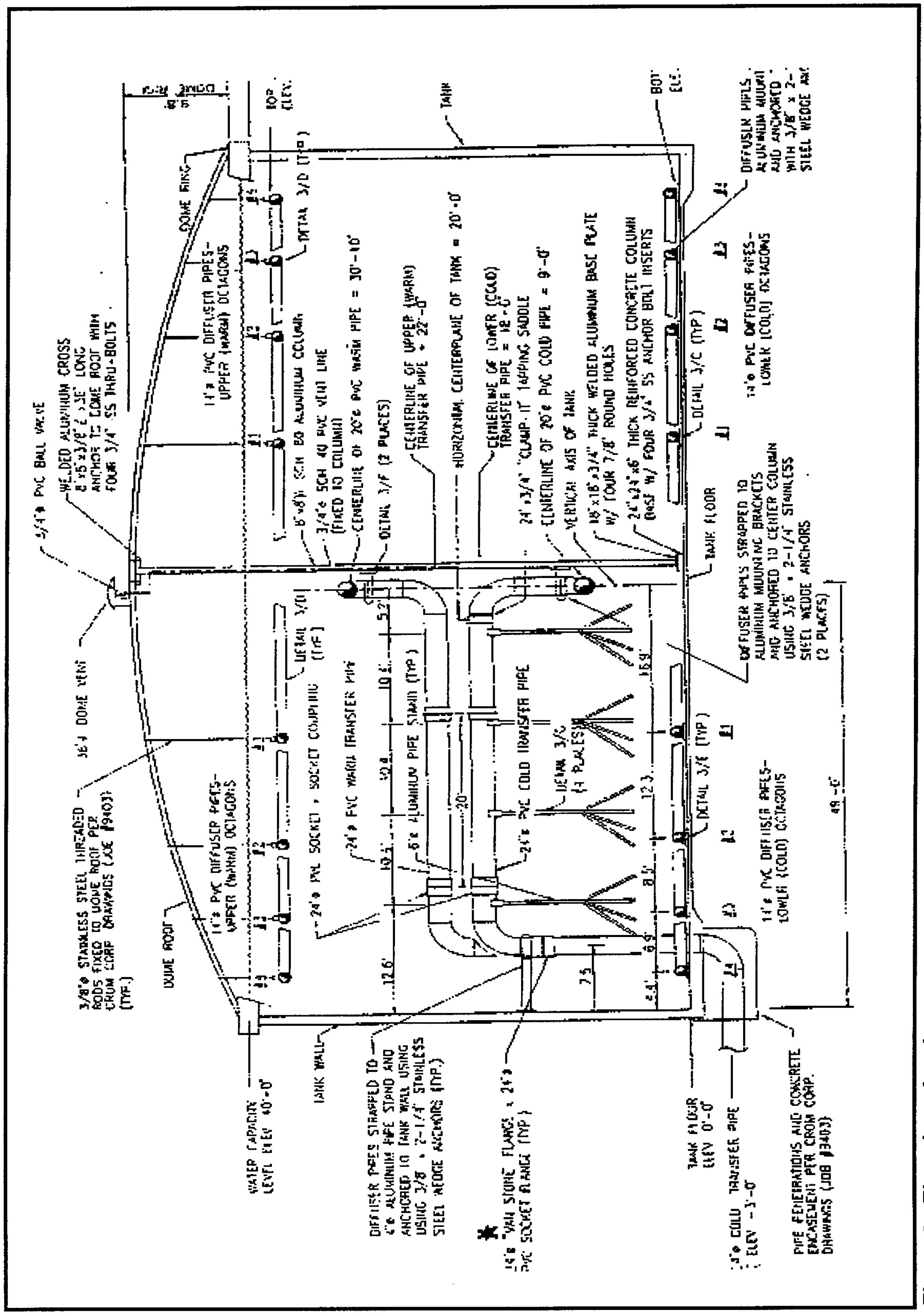

Figure 2. Elevation of tank.

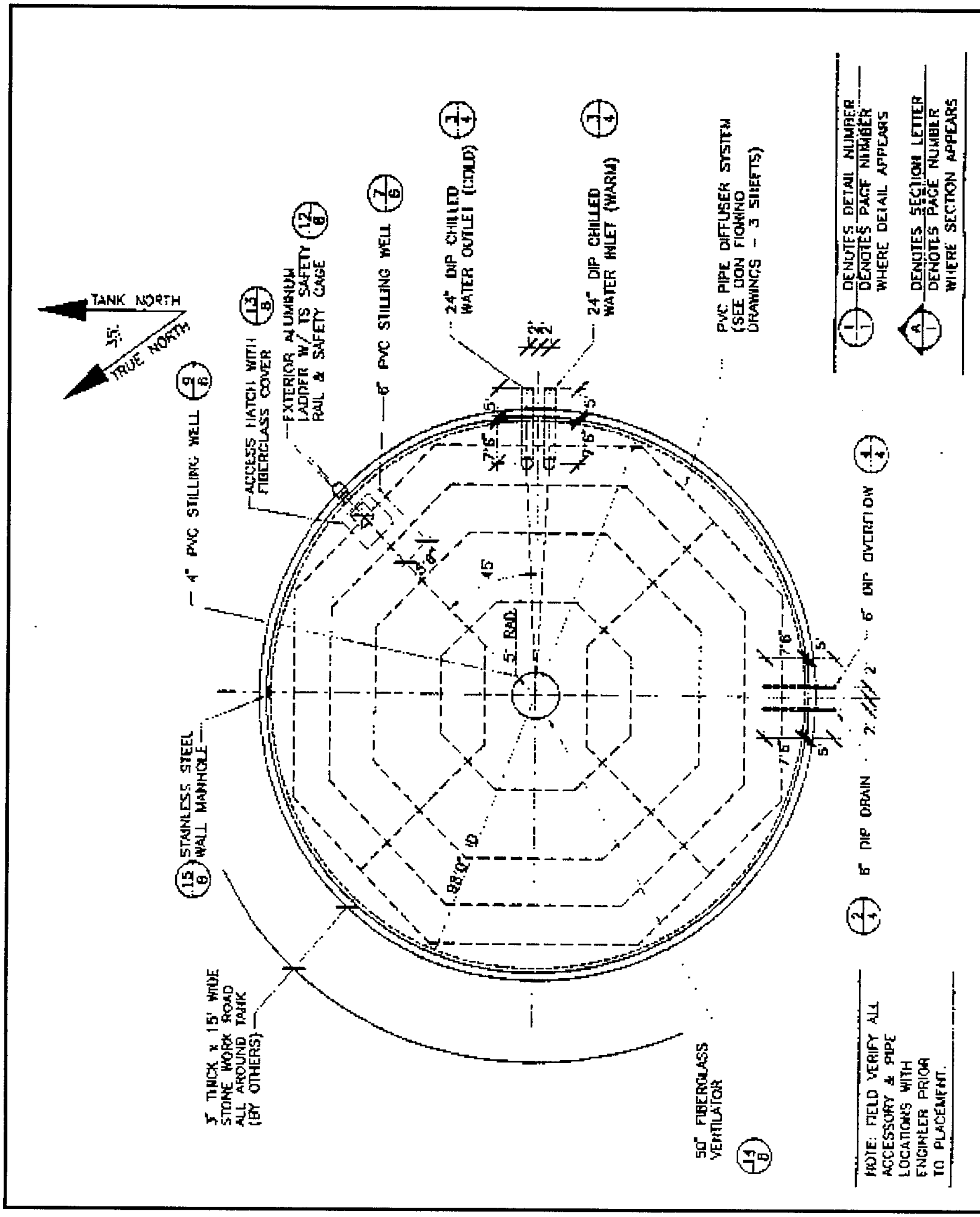

Figure 3. Tank plan.

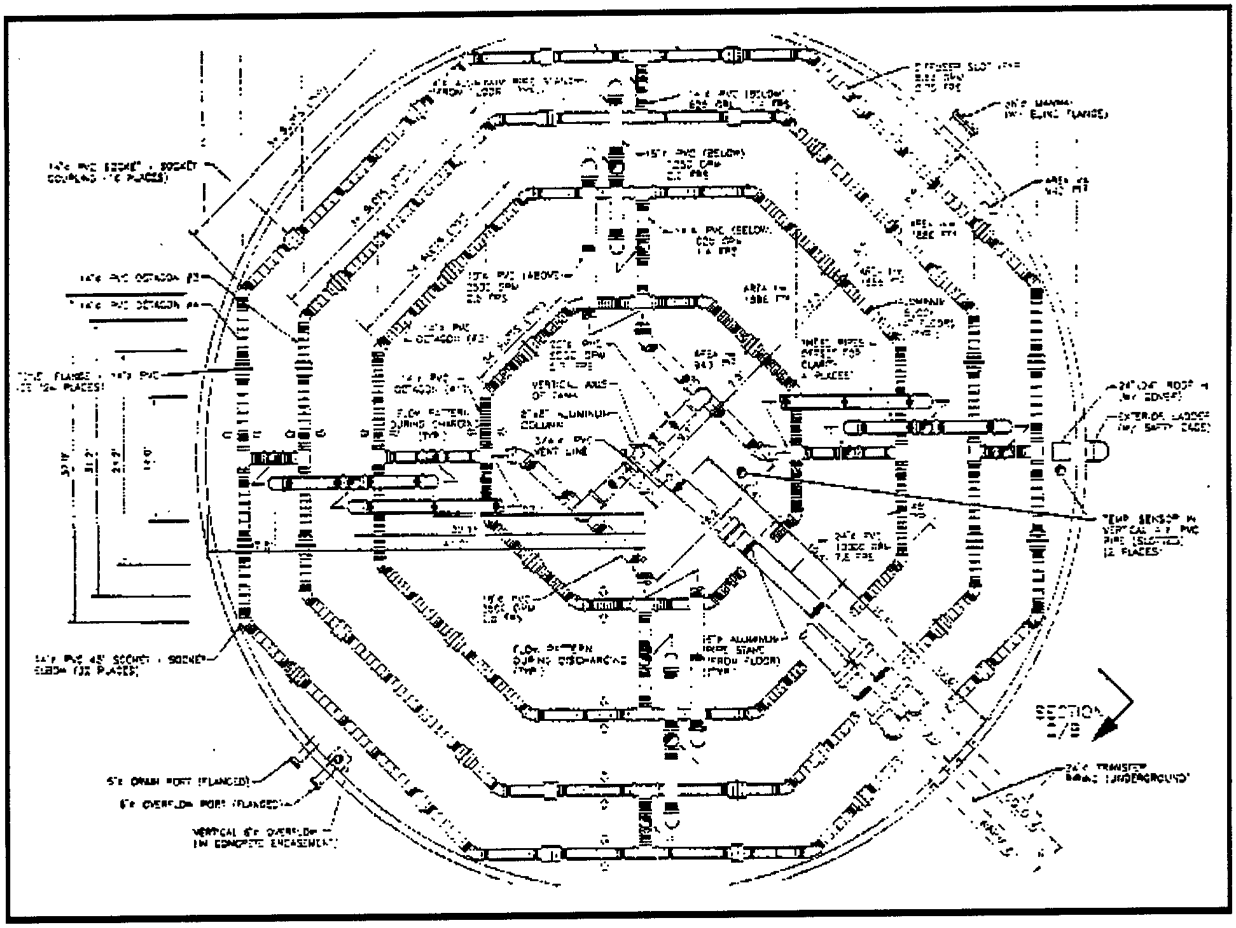

Figure 4. Details of diffuser system.

Table 2. Diffuser characteristics.

Design inlet temperature during discharge cycle	54 °F
Design outlet temperature during discharge cycle	42 °F
Design inlet temperature during charge cycle	41 °F
Reynolds number	811 (2,000 design)
Design Froude number	0.5
Each diffuser pipe flow rate	0.7 cu ft/sec
Number of slots in each diffuser pipe	34
Flow rate of each slot	0.0206 cu ft/sec
Cross-sectional diffuser area	1.0 sq ft
Slot area	0.0294 sq ft
Slot inlet/exit velocity	0.70 ft/sec
Slot width	3/8 in.
Slot length	11.4 in.
Length of each diffuser pipe in octagon #1	14.0 ft
Length of each diffuser pipe in octagon #2	24.2 ft
Length of each diffuser pipe in octagon #3	31.2 ft
Length of each diffuser pipe in octagon #4	37.0 ft

The Reynolds number was calculated as:

Re = (0.01310 sq ft/sec)/(0.00001615 sq ft/sec) = 811

This Reynolds number value was less than the design maximum allowable (2000) recommended in the industry standard design guide (ASHRAE 1993).

The Froude number is defined as the dimensionless ratio of the inertia force to the buoyancy force acting on a fluid. Gravity currents, which are necessary for the proper performance of the tank, will form for Froude numbers less than 1 with limited mixing. The Froude number criterion is used to determine the required inlet height of the diffuser. For a diffuser close to the bottom of the tank, the inlet height is defined as the distance from the tank floor to the top of the diffuser inlet opening. For a chilled water tank, the Froude number is defined as:

$$Fr_i = q/[gh^3(\rho_i - \rho_a)/\rho_a]^{1/2} \qquad \text{Eq. 1}$$

where:

q = volume flow rate per unit diffuser length

g = acceleration of gravity

h = minimum inlet opening height

ρ_I = density of inlet water

ρ_a = density of ambient water

and

$$q = Q/L \qquad \text{Eq. 2}$$

where:

Q = maximum flow rate

L = effective diffuser length.

A Froude number of 0.5 was selected for design of the inlet opening height. Other values necessary for the calculation included:

q = 0.01310 sq ft/sec

g = 32.17 ft/sec^2

ρ_i = density of inlet water

ρ_a = density of ambient water.

Solving for the inlet height yielded a value of 0.35 ft (which, in the final design, was set at 4 in.). The bottom of the lower diffusers were placed 2 in. above the tank floor. The top of the upper diffusers were placed 4 in. from the free surface in the original design.

System Schematics

Four primary chilled water pumps (PCWP) serve the chillers. Two regenerative turbine pumps (RTP) serve the chilled water tank and one heat exchanger pump (HEP) serves the heat exchanger for free cooling application. Also included are four system chilled water pumps (SCHP). Each of the pumps has the characteristics described in Table 3. Two-way, two-position, normally open electric solenoid actuated pneumatic valves are located at each of the four PCHPs. Temperature sensors were mounted inside the storage tank to measure the vertical temperature profile and thermocline thickness in the tank. Figure 5 shows a schematic of the chilled water storage system.

System Construction

Construction of the system was accomplished in two phases. In the phase 1, the tank with internal diffuser system was built in 1994 (Figure 6). Figures 2 (p 13) and 3 (p 14) show the plan and elevation of the tank with the internal diffuser system installed inside the tank. Figure 4 shows the layout of the diffuser segments. Note that the top and the bottom diffusers are a mirror image.

Phase 2 consisted of adjusting the piping inside the energy plant (CEP No. 2) and the pipe connection from the storage tank to CEP No. 2 during the off-cooling season of 1995-96. The phase 2 work was completed in March 1996. During the commissioning of the tank to the cooling loop of CEP No. 2, a major breakage of the upper diffuser assembly inside the tank was detected. Figure 7 shows a typical breakage of the diffuser. The tank was drained, the cause of failure was investigated, and the upper diffuser assembly was repaired for a successful system commissioning on 20 May 1996.

Table 3. Chilled water system pump characteristics.

	RTP	PCHP	SCHP	HEP
GPM	2,000	2,060	2,600	2,000
Total head (feet)	70	25	175	35
Max horsepower	80	20	150	20
RPM	1,750	1,170	1,750	1,170

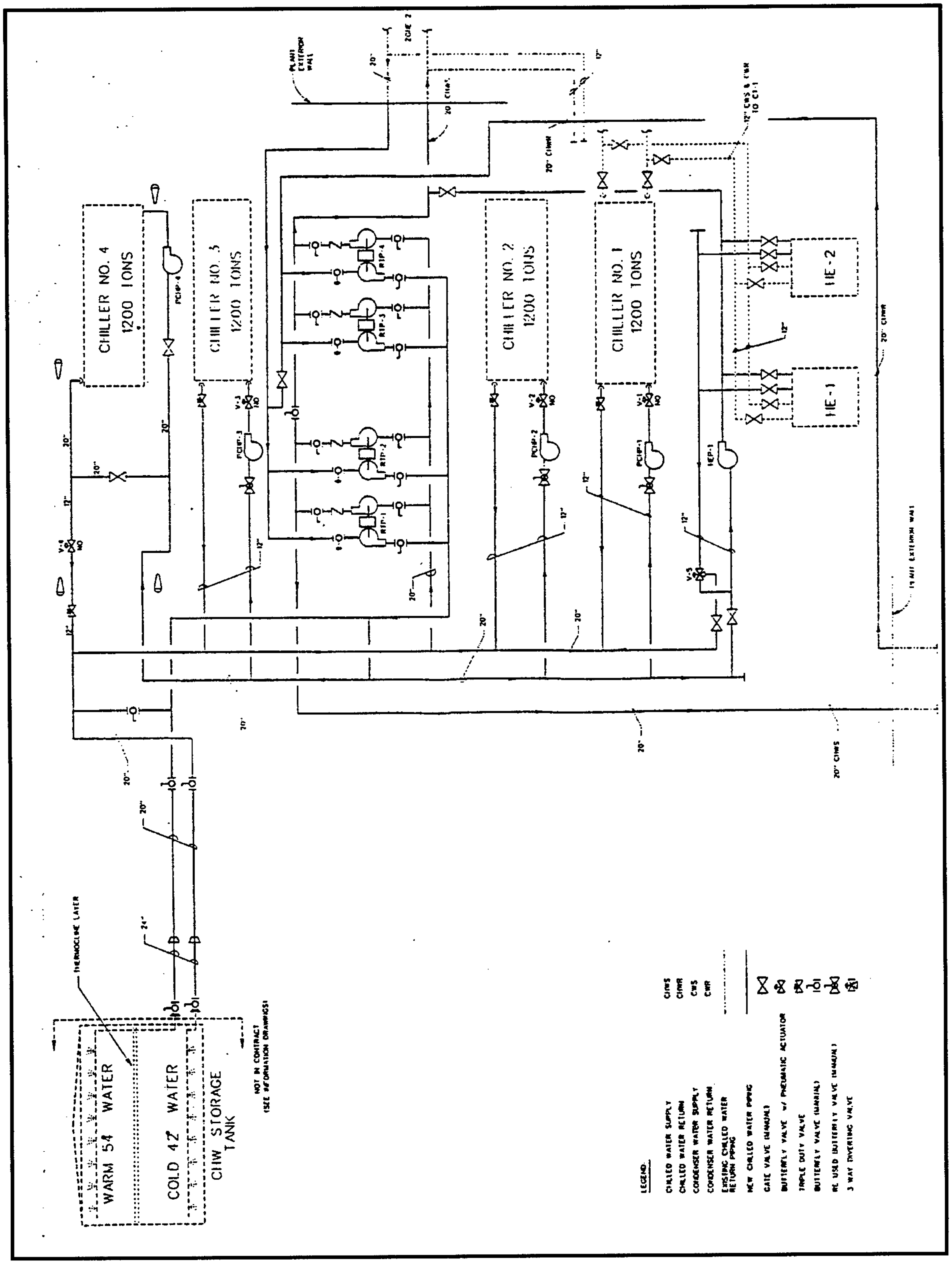

Figure 5. System schematic diagram.

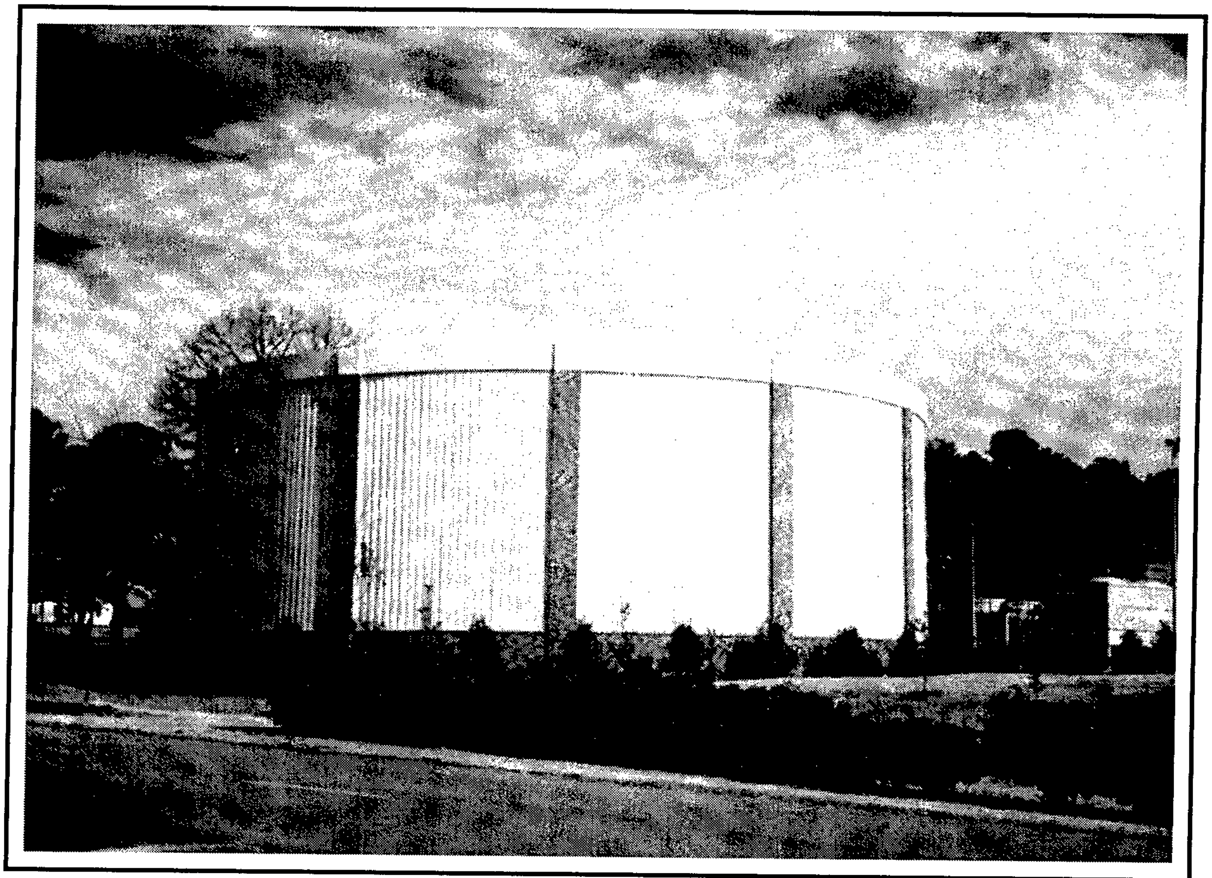

Figure 6. 2.25M gal chilled water storage tank at Fort Jackson, SC.

Figure 7. Breakage of upper diffuser assembly.

System Commissioning

Breakage and Repair of Upper Diffuser Assembly

Note that the upper distribution diffuser system (shown in Figure 2, "Elevation of Tank") is hanging from the ceiling with 3/8-in. stainless steel threaded rods fixed to the dome roof. About 26 breakage points in the upper diffuser system, including diffuser and riser (feeder line to diffuser), were noticed (see Figure 7). The postulated causes of failure and repairs made are:

1. *Buoyancy on the diffuser due to air pocket.* When the tank was initially filled with water, the tank was not connected to CEP No. 2. Water was introduced through the opening at the ceiling. The two 24-ft main transfer lines (to and from the tank, shown in Figure 2) remained closed by isolation valves. Water was introduced into the diffuser assembly through the slots into the closed pipe space. The lower diffuser assembly is anchored to the concrete floor with aluminum mounting pads between the diffuser and floor. The pad and anchor holds the lower diffuser assembly securely against any potential buoyancy forces. On the other hand, the upper diffuser is secured by the 3/8-in. rods, which cannot provide resistance to compression induced by potential buoyancy force due to air pocket inside the upper diffuser assembly. The solution was to install a bypass line across the two 24-in. main transfer lines. A short 11-in. piping with a shut-off valve in the middle was installed between the two main transfer lines just outside the tank. When filling the tank, the bypass line will equalize the rising water level between the inside and outside of the diffuser system, thereby eliminating any potential buoyancy effects.

2. *Valve actuating speed.* Line-sized butterfly control valves are installed at the outlet of recovery turbines in CEP No. 2. The opening speed of these valves was so fast that it could induce water hammer effects along the line, including the diffusers inside the tank. The solution was to slow the valve opening and closing speed to 60 seconds for full opening and closing the valves.

3. *Loose connection of main transfer line to upper diffuser.* The flange bolts connecting the 24-in. steel main transfer line from CEP No. 2 to the 24-in. PVC line to the upper diffuser assembly (marked with an asterisk [*] in Figure 2) within the tank were missing nuts underneath the flange. The loose connection would have generated a significant flow-induced vibration of the upper diffuser structure when a full charge flowrate was introduced to the tank. The flange nuts were installed and tightened for a secure connection of the 24-in. main transfer line for the upper diffuser.

4. *Leveling of Upper Diffuser.* The broken parts of upper diffuser were fixed and the tank was fully charged with city water. One major concern was the levelness of

upper diffuser segments. A DPW engineer entered the tank and measured the elevation of high spots along the diffuser segments. The maximum elevation differential at the highest spot was measured to be 5 in. The original design water depth between the top surface of water and the highest point in the diffuser was 8 in. With the unevenness of up to 5 in., the operating water depth would be reduced down to 3-in. at the highest spot. In case of potential rapid loss of water in the system, e.g., a rupture in the distribution line, the 3-in. margin was deemed too shallow to prevent potential exposure of diffuser slots to atmosphere. Exposure of slots to open air will result in the introduction of air into the circulation system. The solution was to raise the operating tank water level by 7 in. by extending the overflow level from 40 ft to 40 ft 7 in. The tank builder was consulted for the safety of heightened level of water inside the tank, and confirmed the safety of the tank with the increased level of 7 in.

Commissioning of System

The tank was fully filled with city water. Chillers in CEP No. 2 completed charging the tank with chilled water during the weekend of 18 May 1996. The tank was fully charged by early morning 20 May (Monday). The temperature profile inside the tank ranged from 40 °F at the bottom to 43 °F at the top.

The ambient temperature in Columbia, SC on 20 May reached 99 °F. By noon, all four chillers (1200 ton each) in the Energy Plant No. 2 were running to provide cooling for Fort Jackson. Starting from 1222 (20 May 1996), all four chillers were shut down: No. 1 chiller at 1222, No. 2 at 1252, No. 3 at 1307, and No. 4 at 1320. Note that the utility on-peak hours for Fort Jackson are between 1300 and 2100. The chilled water in the tank met the entire cooling load during the peak hours. Chillers were brought back online starting at 1622 for No. 1, 1007 for No. 2, 1722 for No. 3, and 1807 for No. 4. This operation helped Fort Jackson keep its on-peak billing demand under 19,550 kW (Figure 8, "Hourly Load Profile of Fort Jackson, 20 May 1996"). On 20 May 1996, the electrical demand was peaking around 1100 at 23,000 kW. Without the shutdown of the four chillers, the demand should have increased to over 23,000 kW in the early afternoon hours. Therefore, the minimum amount of peak shaving by the storage tank is 3450 kW (the difference between 23000 kW and 19550 kW). Table 4 lists the thermal performance of the tank for the first complete cycle of charging and discharging. The table shows the temperature distribution inside the tank at a number of benchmark hours. Note that, for the first day of operation (20 May 1996), the tank was not fully discharged. Table 4 confirms the regenerating capability of the tank through the night of 20 May. By the morning of 21 May, the tank was fully recharged and ready to repeat the cooling cycle.

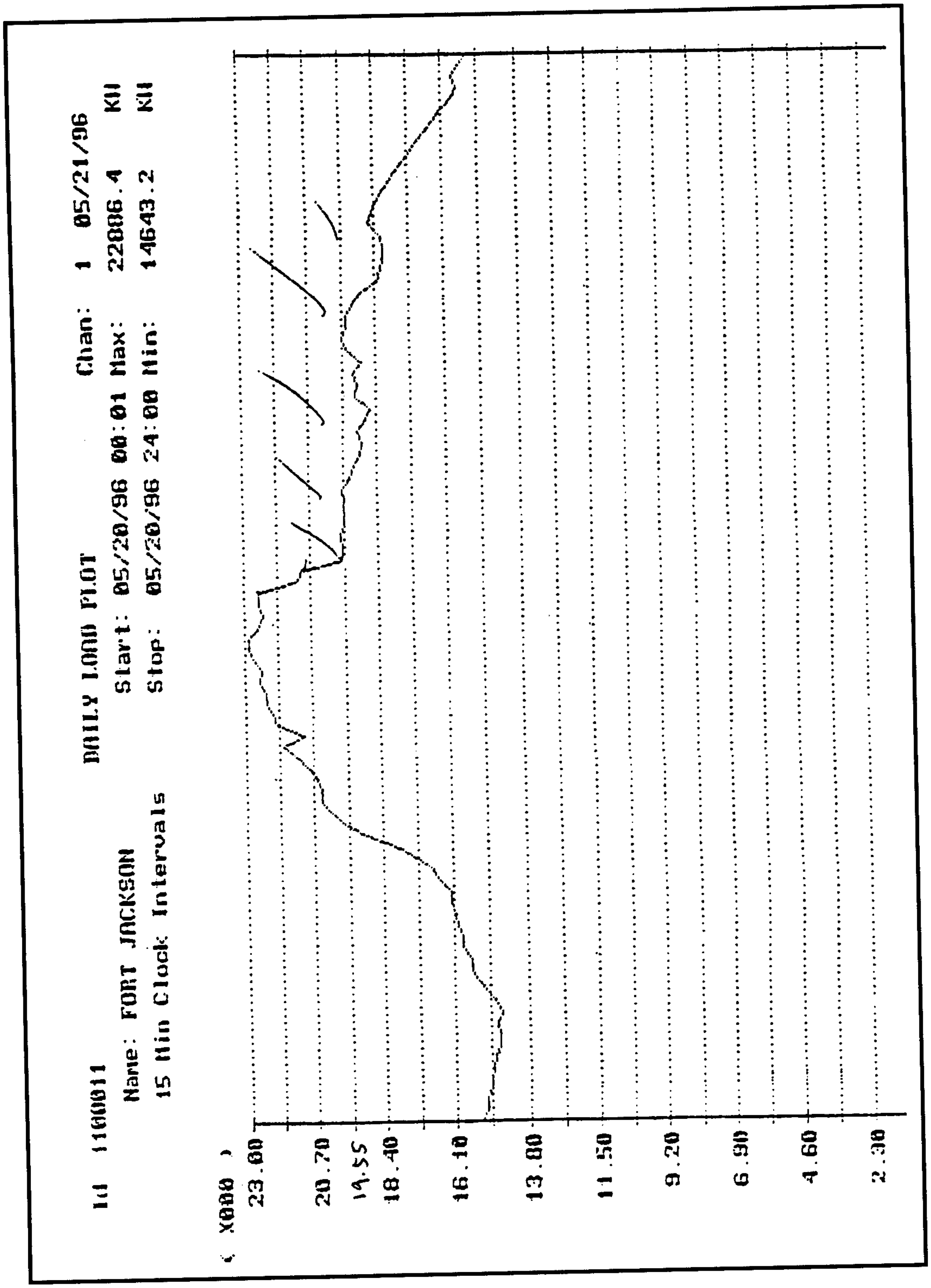

Figure 8. Hourly load profile of Fort Jackson, 20 May 1996.

Table 4. Temperature distributions inside the tank.

Sensor #	Date/Time 20 May 1996 (1710 EDT) °C/°F	Date/Time 21 May 1996 (0830 EDT) °C/°F	Date/Time 22 May 1996 (0830 EDT) °C/°F
20 (top)	13.8/56.9	6.7/44.0	7.3/45.2
19	13.5/56.3	6.7/44.0	7.2/44.9
18	13.2/55.8	6.6/43.8	7.0/44.6
17	12.8/55.0	6.5/43.7	7.044.6
16	11.8/53.3	5.9/42.7	6.4/43.6
15	11.1/51.9	5.9/42.6	6.1/42.9
14	10.6/51.1	5.4/41.7	5.8/42.5
13	10.2/50.4	5.3/41.5	5.8/42.4
12	9.9/49.9	5.3/41.5	5.7/42.3
11	5.5/41.9	4.9/40.9	5.4/41.7
10	4.8/40.7	5.3/41.5	5.7/42.3
9	4.3/39.8	4.8/40.6	5.2/41.3
8	4.2/39.6	4.7/40.4	4.9/40.9
7	*data missing*		
6	*data missing*		
5	*data missing*		
4	4.8/40.7	4.8/40.6	5.5/41.9
3	4.9/40.9	4.8/40.7	5.7/42.2
2	4.9/40.9	4.7/40.4	5.5/41.9
1 (bottom)	*data missing*		

3 System Operation and Performance

First Year Operation of System

Since 20 May 1996, the tank operated as a part of the CEP No. 2 cooling system through the end of 1996 cooling season. During early May 1996, while repairing the diffuser, corrosion of aluminum parts installed inside the tank (i.e., support structure and pads for the lower diffuser segments) was observed. By late May 1996, the cooling load of Fort Jackson became a significant contribution to the peak electrical demand. Due to lack of time, it was decided to bring the tank on line to serve out the 1996 cooling season, after which the aluminum parts would be checked again to determine if further actions were needed at the end of the 1996 cooling season. Note that the corrosion of support members is not related to the thermal performance of the chilled water storage systems.

At the end of the 1996 cooling season, the tank was drained to inspect the integrity of the components inside the tank. On 23 January 1997, the progress of corrosion on the support structure due to dissimilar metal contact inside the tank was examined by CERL and DPW engineers. The rate of progress was determined to be slow enough not to warrant immediate replacement of the supporting parts. A decision was made at the field inspection that the system would be operated without any replacement of components for the next 5 years. It was recommended that the tank be drained at the end of the 2001 cooling season and inspected for any needed remedial actions. To prevent further corrosion damage, the tank water was treated for corrosion inhibition at the beginning of 1997 cooling season. The treatment formula, recommended by CERL and the U.S. Army Corps of Engineers Installation Support Center (CEISC) were:

1. For aluminum: stainless steel and steel components is: Poly Silicate with SiO_2 to NaO_2 ratio equal to 3.22. The dosage is 200 ppm as SiO_2 (Liquid).

2. For copper: Toly Triazole (TT) 50 percent sodium tolytriazole. The dosage is 50-100 ppm.

System Performance

The electrical cost savings by the operation of the CWS cooling system for a year (June 1996 to May 1997) was estimated based on the monthly electrical utility bills for Fort Jackson. Table 5 lists the monthly billing demands for Fort Jackson during the past 4 years. Note that the annual peak demand for Fort Jackson has been reduced from 25,358 kW in 1995 to 23,424 kW in 1996 with operation of the CWS cooling system.

Electrical Cost Savings in 1996-97

Table 6 lists the monthly electrical energy consumption for Fort Jackson during the past 4 years. For each 12-month period (June through May), the annual total energy consumption is 114.84 GwH in 1994-5, 122.69 GwH in 1995-6, and 120.2 GwH in 1996-97. Note that the total energy consumption depends on the level of installation activities as well as fluctuating annual climate conditions. Quantitative determination of energy savings cannot be made from the monthly billing information.

Table 7 summarizes the monthly electrical bills for the past 4 years. A monthly bill has two components: one for the demand charge based on the billing demand (in kW) each month (Table 5), and the other for the energy charge based on the monthly energy consumption (in kWH) (Table 6). A sum of the demand charge and the energy charge is the monthly electrical charge for Fort Jackson.

Table 8 summarizes impact of the CWS cooling system on the annual electrical utility cost for Fort Jackson. It shows changes in the electrical cost for each of 12-month (June-May) period during the past 4 years.

Table 5. Monthly billing demand in kW for the past 4 years.

Month	1	2	3	4	5	6	7	8	9	10	11	12
1994	17485	17485	17485	17485	19008	23155	22896	22810	22810	17485	18524	18524
1995	18524	18524	18524	18524	20822	22896	24408	25358	22896	21470	20286	20286
1996	20286	20286	20286	20286	21456	23136	23424	22752	21840	19872	17856	17856
1997	17856	17856	17856	17856	19584	23328	24768	24432	22560	19920	18662	

Table 6. Monthly billing demand in kW for the past 4 years.

Month	1	2	3	4	5	6	7	8	9	10	11	12
1994	17485	17485	17485	17485	19008	23155	22896	22810	22810	17485	18524	18524
1995	18524	18524	18524	18524	20822	22896	24408	25358	22896	21470	20286	20286
1996	20286	20286	20286	20286	21456	23136	23424	22752	21840	19872	17856	17856
1997	17856	17856	17856	17856	19584	23328	24768	24432	22560	19920	18662	

Table 7. Monthly electrical cost ($) for the past 4 years.

Month	1	2	3	4	5	6	7	8	9	10	11	12
1994-KW	116,015	115,805	116,015	121,097	143,260	324,638	321,015	319,811	319,811	128,919	145,558	145,558
1994-KWH	136,472	158,824	144,501	157,874	188,738	291,494	315,226	320,185	268,695	156,891	174,155	156,697
1994 sum	252,487	274,629	260,596	278,971	331,998	616,132	636,241	639,997	588,507	285,810	319,713	302,255
1995-KW	145,558	145,558	145,558	145,558	163,528	321,015	342,168	355,458	321,015	167,698	159,337	159,337
1995-KWH	167,357	165,185	161,245	185,516	211,028	277,848	348,405	324,302	289,389	201,679	169,486	172,565
1995 sum	312,915	310,743	306,803	331,074	374,556	598,863	690,573	679,760	610,404	369,377	328,823	331,902
1996-KW	176,628	193,920	193,920	193,920	202,873	296,885	309,248	299,158	286,737	188,624	170,811	170,811
1996-KWH	159,192	171,092	166,915	177,570	210,167	275,235	321,835	298,411	218,449	241,277	169,937	182,338
1996 sum	335,820	365,012	360,835	371,490	413,040	572,120	631,083	597,569	505,186	429,901	340,748	353,149
1997-KW	172,953	172,953	172,953	172,953	189,107	312,323	327,022	320,113	303,166	190,721	163,378	
1997-KWH	164,450	174,543	171,965	163,332	174,907	278,116	324,871	304,166	296,461	208,501	169,988	
1997 sum	337,403	347,496	344,918	336,285	355,015	590,439	651,893	624,279	599,627	399,223	333,365	

Table 8. Annual electrical utility cost for the past 4 years.

12-month (Jun-May)	Demand cost ($)	Energy cost ($)	Total cost ($)	Demand/Total
1994 – 1995	2,451,070	2,573,674	5,024,744	0.4878
1995 – 1996	2,787,289	2,668,610	5,455,899	0.5109
1996 – 1997	2,603,193	2,556,679	5,159,872	0.5045

For the first 12-month operation of the CWS cooling system, the system reduced the electrical cost for Fort Jackson from $5.46M in 1995-96 to $5.16M in 1996-97. During the 1996-97 period, a number of large buildings were added to Fort Jackson (9 buildings at a total floor area of 342,562 sq ft). Even with the increased electrical energy demand and consumption by these new buildings, the total electrical bill was reduced by $0.3M during the first 12-month operation of the CWS cooling system. Note that the annual electrical utility cost for Fort Jackson has been increasing during the past years, i.e., $5.02M in 1994-95 and $5.46M in 1995-96. Without the CWS cooling system, the trend will continue and the cost during 1996-97 would have been significantly higher than the cost during 1995-96. Therefore, the actual impact of the CWS cooling system on the cost savings will be significantly more than $0.3M. The actual saving is estimated to be close to $0.43M based on the demand-shift capability of the system measured during the field test on 20 May 1996 (see "Economic Performance," p 29).

Thermal Performance of the System

The thermal efficiency of the storage tank depends on the creation and maintenance of a sharp thermocline inside the tank during operation. A snapshot of the thermocline characteristic was plotted with a three-channel temper-

ature recorder (Figure 9). The three thermocouples were located vertically 15 ft apart each inside the tank. The thermocline took 6 hr (from 2320, 23 September 1997 to 0520, 24 September 1997) to travel 30 ft vertically between the bottom and top sensors. That corresponds to a charging flow rate of 4688 gpm, which yields the charging inlet Reynolds Number of 760, based on the total diffuser length of 851 ft.

It is widely accepted that a charging Reynolds Number of less than 1000 establishes and maintains a good thermocline inside the tank (ASHRAE 1993). Figure 8 shows movement of a sharp thermocline inside the tank during the charging process through the night of 23-24 September 1997. The calculated depth of the thermocline ranges from 1 ft at the bottom level, and 1.5 ft at the mid-level and 2 ft at the top level in the tank. Based on a conservative 2 ft thickness of thermocline, a theoretical charge efficiency of the tank is calculated to be 95 percent (38/40). A sharper thermocline is expected to yield a better storage efficiency. The measurements of thermocline movement inside the tank (Figure 8) demonstrate the diffuser system is working properly. It is believed that a large number of similar systems are operating with the thermocline thickness in the range of up to 5 ft. For the Fort Jackson system, creation and maintenance of thermocline with a thickness less than 2 ft shows an excellent thermal performance of the system.

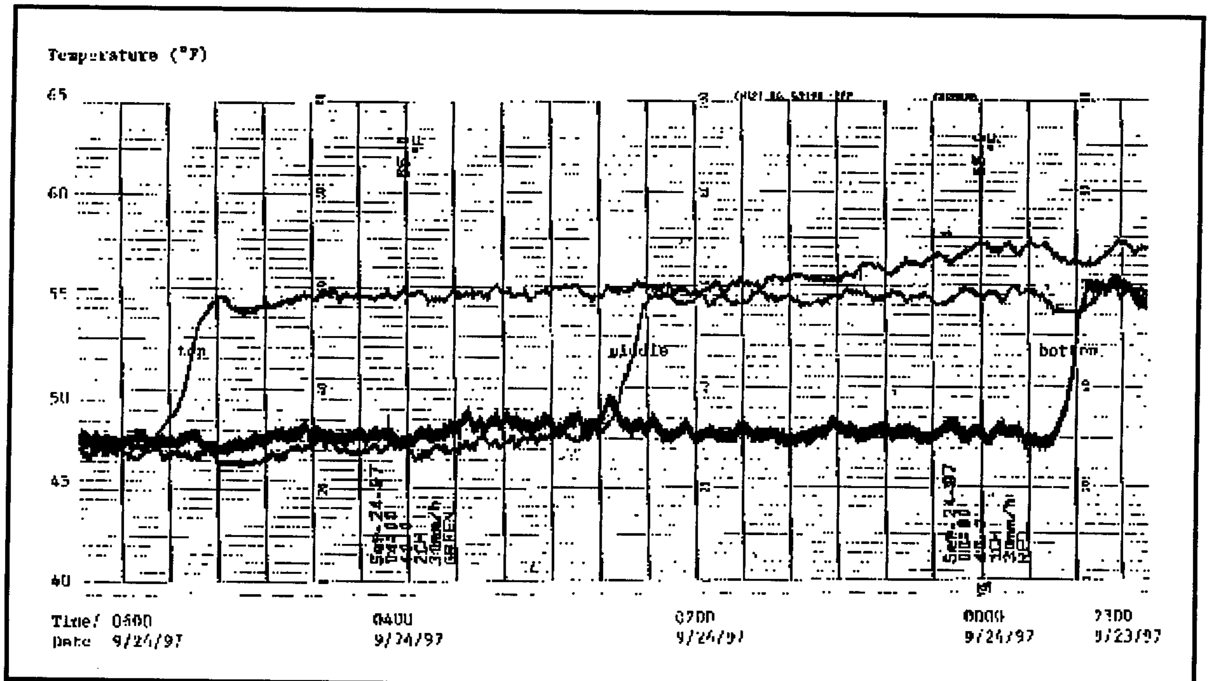

Figure 9. Profile of thermoclines within the tank.

Economic Performance

The most significant benefit of the CWS cooling system is reduction in annual on-peak electrical demand of Fort Jackson. Due to the increasing level of activities at Fort Jackson, the annual peak demand has been growing 23,088kW in 1989 to 25,358kW in 1995. Commissioning of the system at the beginning of 1996 cooling season reduced the annual peak demand to 23,424 kW in 1996, thereby reducing the on-peak electrical demand by 1,934 kW compared to the year before. During the first 12-month (June 1996-May 1887) operation of the system, the annual electrical utility cost for Fort Jackson has been reduced from $5.46M in 1995-6 to $5.16M in 1996-7 period. Note that during the 1996-7 period, a number of large buildings (of the total floor area 342,562 sq ft) were added to Fort Jackson inventory, which increased consumption of electricity. Therefore, actual savings during the first year of operation is a sum of $0.3M (savings reflected in the monthly bills), the increased electrical utility costs incurred by the new buildings brought on-line during the 1996-7 period, and yearly inflation of electrical utility cost.

A more realistic cost saving can be estimated from the commissioning data (Figure 8). By the time all four chillers in the Plant No. 2 were unloaded at 1320, 20 May 1996, the electrical demand registered at the Fort Jackson master meter had dropped from 23,000 kW at 1100 to 19,550 kW at 1320. This shows the system capability in demand reduction by 3450 kW. Each of the four chillers is rated at a 1200-ton capacity. For a total cooling tonnage of 4800 ton, the electrical demand of 3450 kW yields the chiller kW/ton ratio of 0.72 kW/ton, which is quite reasonable for the centrifugal chillers. Based on the demand reduction of 3450 kW and the prevailing electrical rate structure of the South Carolina Electric and Gas Company, the annual cost savings is estimated to be $0.43M/yr.

4 Discussion

Project Execution

An implementation of chilled water storage (CWS) to a central energy plant (CEP) requires a careful project schedule. An immediate concern is that a CEP typically serves a large number of cooling customers. Therefore its operation cannot be disrupted, especially during the cooling season. For the Fort Jackson project, the connection of the tank to the CEP No. 2 in the late spring of 1995 was seriously considered as an option. There were three options: (1) no cooling during the pipe connection work up to 1-1/2 weeks, (2) a temporary cooling provision, or (3) delay of the project until the end of the cooling season. The first option was unacceptable to Fort Jackson. A quote for the temporary cooling during the outage of CEP No. 2 was received at a cost of $1.07M, based on a 6-week period, including setup and teardown. Due to high cost of the option, the project was delayed until the end of 1995 cooling season. By the time when the Phase II was completed in March 1996, the 1-year warrantee on the tank construction had expired. When the breakage of the upper diffuser assembly was found out in March 1996 (See "System Commissioning," p 20), it was not clear when the failure had occurred, during the testing of the tank in early 1995 or during the commissioning test in March 1996. Completion of the project by a single source contractor would have avoided such confusion.

Design and Construction

The diffuser system inside the tank is the most critical element in successful performance of CWS cooling system. The octagonal diffuser system used in the Fort Jackson system (Figure 4) yielded excellent performance, as Figures 8 and 9 show. It was designed following the recommended design criteria of inlet Reynolds number less than 850, as suggested in the current industry design guide by the ASHRAE (1993). According to the ASHRAE guide, "For tall tanks, 40 ft (12 m) deep or more, there is evidence that diffusers with inlet Reynolds number of 2,000 or more may provide acceptable stratification. For design purposes, a maximum of 2,000 for the Reynolds number should be used. In

general, an upper limit of 850 is recommended, unless data are available for a specific tank to support proper stratification at higher Reynolds numbers."

The strict requirement in the inlet Reynolds number criteria (less than 850) resulted in a rather complicated diffuser system (quadruple octagonal diffuser, Figure 4) for the Fort Jackson system.

For future applications, a double octagonal diffuser is recommended for a cylindrical tank. The double octagonal configuration will reduce the total length of the diffuser by a factor of two, thereby raising the inlet Reynolds number of a quadruple octagonal configuration by the same amount. The Reynolds number criteria may be increased up to 2000 for future tanks of height at least 40 ft tall. Careful attention should be given to the number and size of slots for each diffuser segment. For the Fort Jackson system, the total cross-sectional area of slot outlet was designed to be the same as that of the 24-in. main transfer pipe. Operators at Fort Jackson expressed concerns for increased pressure drop across the tank loop. For future design, the total cross-sectional area of slot outlet will be designed to be a minimum of 150 percent of the cross-sectional area of the main transfer line. The increased outlet area will reduce the pressure drop across the tank and will reduce the outlet jet speed to achieve a better thermal stratification. Study of an optimal design Reynolds number is ongoing. Preliminary results will be available to the design community in early 1999 (ASHRAE 1998).

The Fort Jackson system experienced significant corrosion of aluminum components inside the tank. Careful attention should be given to the specifications of material inside the tank to avoid potential corrosion. Generally speaking, aluminum and copper components are not recommended inside the tank. A bypass line between the two main transfer lines to the tank should be installed right before entrance to the tank. The segment should be equipped with a manual butterfly valve to isolate the two main transfer lines during normal operation. The valve will remain open only during the filling and draining of the tank to eliminate potential air pockets inside the diffuser system. The size of the bypass line could be half of the main transfer line, which showed itself to work well for the Fort Jackson system. To avoid potential water hammer damage, all the valve actuators must be slow acting. Use of an adjustable speed drive for main circulation pumps is a good approach to avoid fluid transient problems and to provide optimal control for cooling service. Close inspection of construction workmanship to match the design specifications is important for the project's success. Special attention should be given to the

construction and installation of diffuser segments and leveled installation of upper diffuser assembly.

Commissioning and Operation

The commissioning process should begin with a final inspection of workmanship and acceptance testing of the system. The most critical phase is the initial filling of the tank with city water. An accurate reading of flowmeter in the main transfer line is a critical item to be verified. The contractor should have developed a detailed procedure for filling the tank to avoid damage to the structure inside the tank. Tank integrity should be tested with a fully charged tank. The operation of a level sensor should be checked when the tank water level reaches near the design height. A proper operation of the level sensor is critical to avoid potential exposure of upper diffuser slots to the atmosphere during an emergency loss of water from the system. Note that the tank is a part of the entire cooling loop; any loss of water (at the building or along the distribution line) will result in a lowering of the tank level unless makeup water is supplied on time. A dial pressure gauge located at the bottom of tank is a useful guide to check the filling rate into the tank.

Water should be treated as local requirements specify. Note again that the water in the tank is circulating along the entire cooling loop, including distribution systems and buildings. Treatment of water for required protection of coils and pipes should be equally applied to the water filled into the tank.

When the tank is completely filled with city water, the temperature sensors (installed at 2-ft intervals from top to bottom) should provide uniform temperature distribution vertically. It is critical to verify accurate reading of temperature sensors and flow meters installed in the main transfer lines for acceptance testing and for future successful operation of tank. Together, flow rate inside the main transfer line and the differential temperature between the two main transfer lines, determine the amount of cooling stored into the tank and cooling delivered by the tank. Once again, this emphasizes the importance of a flow meter in the main transfer line and temperature sensors across the two main transfer lines. A project implementation guide by ASHRAE (1996) details further recommendations for acceptance and commissioning testing.

5 Conclusion

Fort Jackson, USACE Savannah District, and CERL designed and built a large capacity (2.25M gal) chilled water storage cooling system for the Central Plant No. 2 at Fort Jackson, which serves more than half of Fort Jackson's cooling load. The system completed a successful operation for 2 years, resulting in an annual electrical utility cost savings of $0.43M for Fort Jackson. The system performed successfully, exceeding the original design goal of shifting 3000 kW of on-peak demand to off-peak periods. Results of commissioning testing done on 20 May 1996 showed that the system reduced Fort Jackson's post-wide electrical demand by 3450 kW when the four chillers in CEP No. 2 were unloaded with cooling provided by the storage tank. A review of the monthly electrical utility bills showed a significant reduction of Fort Jackson's growing annual electrical on-peak demand.

Valuable lessons were learned during the system's design, construction, and operation, specifically regarding:

1. Tank sizing (p 9)
2. Tank configuration (p 10)
3. Internal diffuser design (p 11)
4. Corrosion prevention (p 24).

Two more chilled water storage cooling systems are currently under construction by the Savannah District: one for the CEP No. 1 at Fort Gordon, GA, and the other for CEP No. 1 at Fort Jackson, SC. Lessons from the Fort Jackson CEP No. 2 project will serve a useful guide for successful construction and operation of these systems.

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